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Design of Auxiliary Water Systems for Fishways

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Abstract*: The German Waterways and Shipping Administration (WSV) is responsible for the restoration of upstream migration of fish at the federal waterways. For that purpose, a large number of fish passages have to be built in the near future. As federal waterways are usually characterised by large channel widths, it is an important aspect that fish find the entrance of a fishway. The sensory capabilities of fish are manifold. However, it is generally accepted that fish mainly orientate on the flow during their upstream migration. In this respect, the attraction flow of a fishway in the tailwater of a dam becomes relevant as its purpose is to compete with the flow of a hydro power plant or a weir discharge. Following this, the basic flow of a fishway is not sufficient at larger dams, so that auxiliary flow has to be added through screens in the side walls of the fishway entrance pool. As the added discharge may exceed the basic discharge of the fishway significantly, it is important to design the auxiliary water system in a way that the swimming behaviour of fish is not influenced negatively. Generally accepted design recommendations for auxiliary water systems in fishways are virtually non-existent. At the Federal Waterways Engineering and Research Institute (BAW), physical and numerical model studies have been carried out that focus on the hydraulics of auxiliary water systems. The requirements given by fish biologists define a flow with low velocities and turbulence intensities. As the auxiliary water is usually taken from the head water of a dam, the energy height of the flow adds up to some few metres. Consequently, the main challenge is to work up technical solutions under difficult conditions with a severe lack of space. In a first step, technical solutions were developed for pilot sites that are currently in the planning stage. Afterwards the study aims to extend these technical solutions to a broad range of boundary conditions.*

Keywords: *Fish, upstream migration, physical modelling, mixing, auxiliary water system, flow expansion, hydraulic structures*

1. Introduction

Slowing the movement of water in the tailwater of a dam or barrage under constricted site conditions is a frequently occurring challenge for hydraulic engineers, as for example for stilling basin design or for filling-systems at ship-locks. In context of fishways, this subject is relevant for the design of auxiliary water systems. For large rivers, it is widely accepted that in addition to the basic flow of a fishway water must be supplemented to guarantee an adequate hydraulic signal in the tailwater of a dam, guiding fish into the fishway (Weichert et al., 2013, Gisen et al, 2017). As current knowledge suggests adding this water into a pool of the fishway structure, a number of difficult challenges have to be addressed.

Usually, the auxiliary water is taken out of the headwater of the dam and transferred by a channel or pipe system to the entrance pool (**Figure 1**). Therefore an intake-structure, a transmission line, an energy dissipation structure and a supply structure that adds the auxiliary flow into the fishway entrance pool are necessary (these four components are defined in the following as auxiliary water system). Whereas most parts of the auxiliary water system are fish free zones, at the intake and the supply structure fish interact with the flow. In this respect, flow phenomena are possible which may influence the swimming behaviour and orientation of fish negatively. Generally accepted design recommendations for auxiliary water systems in fishways are virtually non-existent (DWA, 2014). On contract of the Federal Waterways and Shipping Administration, the Federal Waterways Engineering and Research Institute (BAW) is developing technical solutions for the designs of fishways, together with the Federal Institute of Hydrology (BfG) and assigned planning offices (e. g. Heimerl et al. 2015, Hermens & Fiedler 2017).

In the present paper, the focus is on the interface between the transmission line and the supply structure and its influence on the biological criteria defined for the discharge of auxiliary water into the entrance pool. Four different transitions between transmission line and supply structure were investigated in a physical model and evaluated regarding the use in auxiliary water systems.

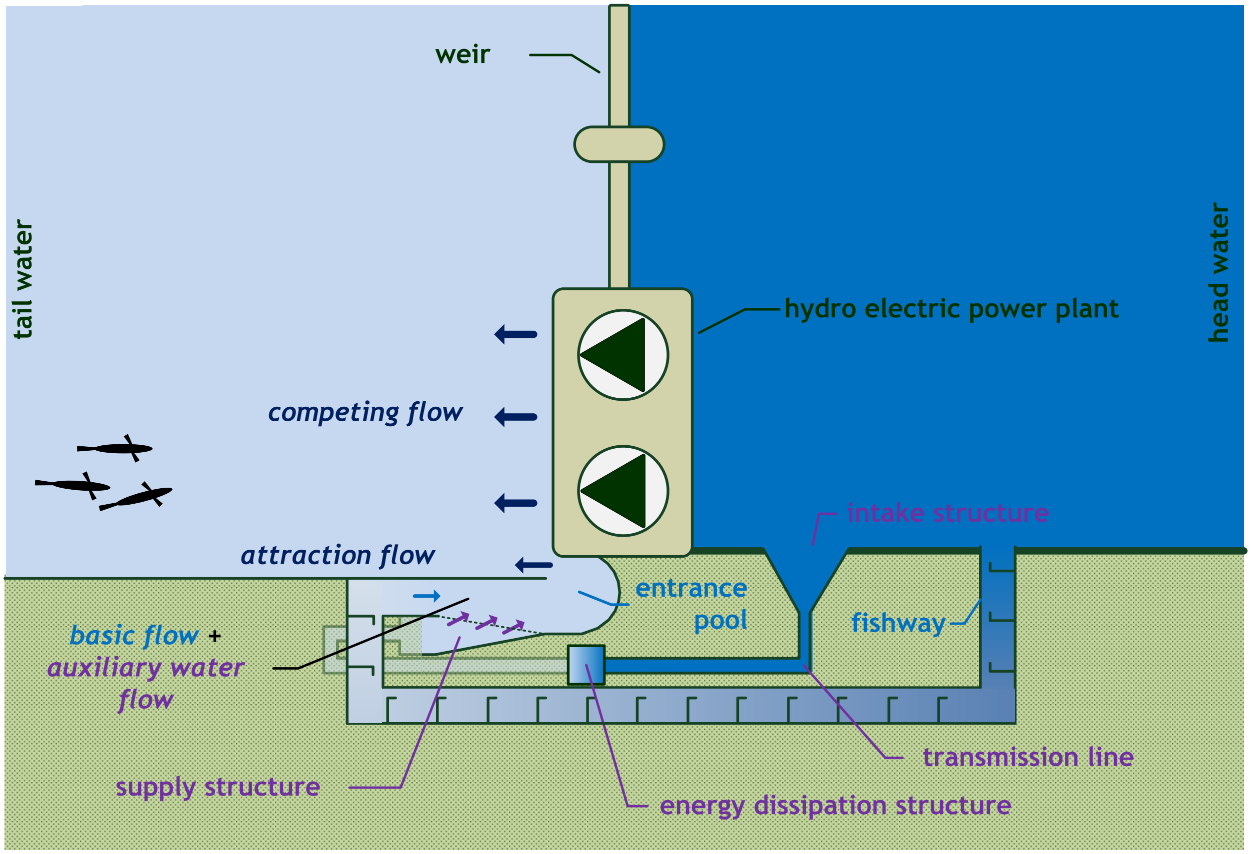

Figure 1: Schematic drawing of an auxiliary water system composed of an intake structure, transmission line, energy dissipation structure and supply structure.

2. Significant Design Specifications

The function of the supply structure is to connect the transmission line system (e.g. a pipe) with the fishway entrance pool. The supply structure is required, as a direct inflow of water transferred from the headwater to the fish entrance pool will not fulfil the criteria defined by fish biologists for flow inside the fish entrance pool. In many cases the added discharge exceeds the basic discharge of the fishway (Weichert et al., 2013). A passage of upstream migrating fish into the supply structure is prevented by a fine screen. A qualitative demand on hydraulics within the entrance pool is that a migration corridor should not be interrupted, i.e. fish is not disorientated by the added discharge. To fulfil this requirement, fish biologists (involved in this study) defined a threshold value for the supply velocity to guarantee that fish are not attracted by the screen outflow instead of passing the entrance pool. As a consequence, biologists set a limit of the orthogonal component of the screen outflow by 0.4 m/s (DWA, 2014). In this context, it is important to distinguish the resultant and the orthogonal flow velocity which are combined by the angle of the supply structure to main flow direction within the fish entrance pool. If, for example, the angle between screen and main flow direction within the fish entrance pool is 30°, the value of the resultant velocity should not exceed 0.8 m/s to hold the threshold value for the orthogonal screen outflow velocity.

Usually flow velocity in the transmission line exceeds the threshold values defined above. Consequently, the cross section area needs to increase to diminish flow velocities. It is evident that the individual component-design of the transmission line and supply structure determines the effectiveness of the homogenisation of flow. In general, flow homogenisation of the outflow of the transmission line is necessary to guarantee a homogeneous distributed orthogonal velocity of 0.4 m/s at the screen.

Another important factor to consider whilst optimising supply structures is turbulence. Quantitative knowledge about the influence of turbulence on fish behaviour is scarce in general and virtually non-existent in entrance pools of fishways. Hence, biologic specifications are qualitative, as flow requirements are usually defined as “calm as possible” and velocity fluctuations should not challenge maximum swimming capabilities of fish.

To assess hydraulic functioning of supply structures, the rate of inhomogeneity and turbulence of the screen-outflow have to be considered. Inhomogeneity-intensity (IH [%]) specifies spatial deviation of the velocity distribution inside the cross-sectional supply area ($\sigma_{spatial}$) divided by the critical value for screen outflow velocity:

$$IH = \frac{\sigma_{spatial}}{v} \times 100 \tag{1}$$

The process of flow homogenisation between transmission line and screen (H [%/m]) can be described by the decrease of IH between two stations x_i along the flow-line:

$$H = -\frac{IH_2 - IH_1}{x_2 - x_1} \tag{2}$$

Turbulence intensity describes the temporal fluctuations inside an arbitrary cross-section ($\sigma_{temporally}$) of flow divided by the critical value for screen outflow velocity to evaluate the flow:

$$TI = \frac{\sigma_{temporally}}{v} \times 100 \tag{3}$$

The process of flow calming between transmission line and screen (C [%/m])) can be described by the decrease of TI between two stations x_i along the flow-line:

$$C = -\frac{TI_2 - TI_1}{x_2 - x_1} \tag{4}$$

These parameters are used to assess and optimise supply structures and to analyse their hydraulic behaviour.

3. Case study about a Lateral Supply with Riser

As mentioned above, auxiliary flow is added through screens in the side wall of the fishway entrance pool (Schütz, 2016, Czerny, 2017), as it is illustrated in **Figure 2**. The screen is arranged acute-angled and the supply direction almost agrees with the flow direction inside of the entrance pool. Previous studies showed that a homogeneous flow distribution at the inflow of the supply structure results in a homogeneously distributed flow field at the screen. Due to site-specific layouts of a fishway a transmission line can be arranged in many different ways. For example, pipe systems that are located underneath the fishway are frequently used. The advantage of this is the constructional separation of the course of the fishway and the transmission line as they are arranged at different elevations. However, such a design requires a riser at the interface transmission line and supply structure to lift the auxiliary water on the elevation of the fishway.

In this context, a case study in a physical model of an auxiliary water system for a maximal flow rate of 6 m³/s was carried out. The goal of this study was to optimise the supply structure by an investigation of different riser-designs and their influence on the screen outflow. Optimisations of the riser structure were developed to generate a fast homogenisation and calming of the riser outflow with the objective to guarantee a homogeneous distributed and calm screen outflow. Normally a pipe elbow is necessary to guide the discharge of the transmission line towards the entrance pool. Thus a pipe elbow is situated upstream of the riser. Contrary to the supply specifications which are described above, the screen in this study was designed for an orthogonal screen outflow velocity of 0.2 m/s. This specification was a special guideline for the associated construction project of the physical model (Fiedler, 2016).

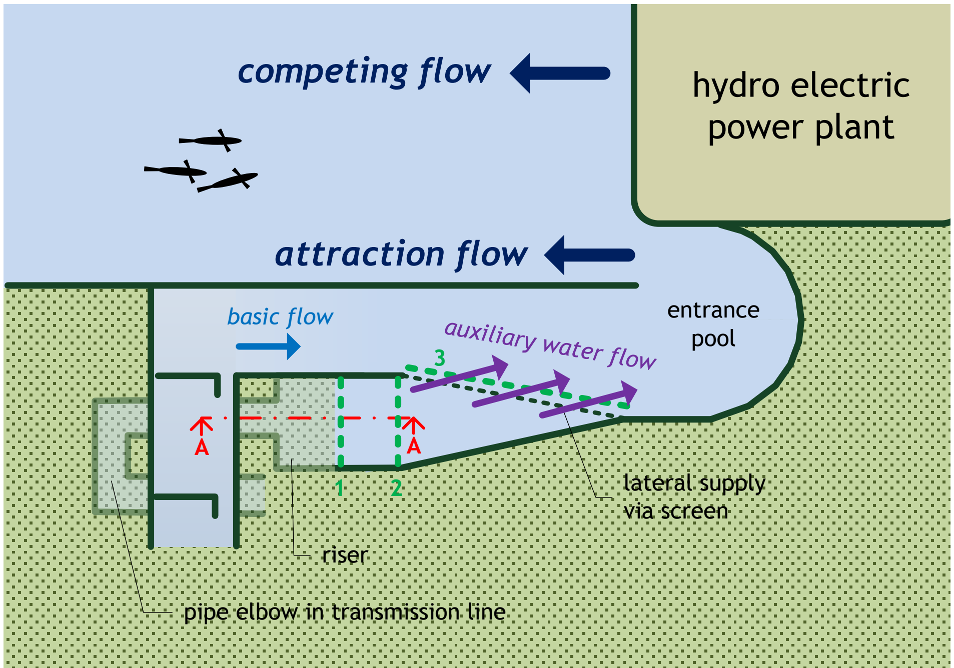

Figure 2: Plan view of an exemplary fishway design with lateral supply; the transmission line is designed as a pipe, arranged at a lower elevation than the supply structure and it leads with a riser into the supply structure; red labelled: longitudinal sections A-A; green labelled: measuring planes 1, 2 and 3.

For the evaluation of the tested risers regarding their screen outflow-distribution, three-dimensional velocity measurements with an acoustic doppler velocimetry sensor were carried out at maximum auxiliary flow rate of 6 m^3/s. For this purpose measuring planes directly behind the riser (1), around 2 m behind the riser (2) and downstream of the screen (3) were analysed in terms of IH, H, TI and C.

In a first step, a very simple riser design in shape of a vertical pipe elbow between transmission line and supply was investigated (**Figure 3**). The outflow of this riser was characterised by a circular jet with high velocities. The jet reached the screen cross-section which results in a strongly inhomogeneous distributed screen outflow (**Figure 5**). As a consequence, the critical values for the screen outflow velocities exceeded the threshold value by many times. So it was necessary to optimise the riser design to find a more suitable connection between transmission line and supply structure. Therefore, different riser designs were tested which are labelled as “slope”, “slope with flow rectifier”, “bottom-step with guide wall” and “bottom-step with guide vanes” (**Figure 4**). The present designs were developed in the scope of a site-specific case study (e. g. Heimerl 2016) together with the assigned planning group of Fichtner Water & Transportation GmbH (Stuttgart) and ARCADIS Deutschland GmbH (Köln). Guide vanes were designed as recommended in Idelchik (2008).

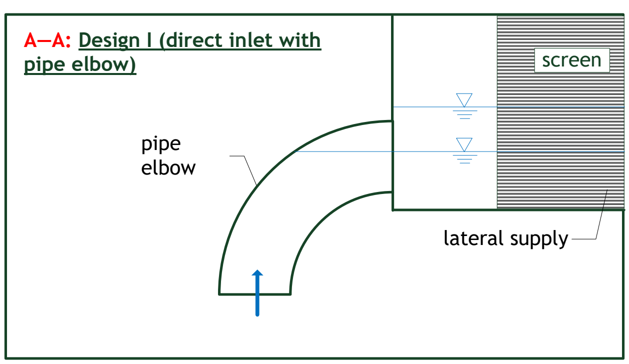

Figure 3: Longitudinal sections A-A of investigated riser-design I.

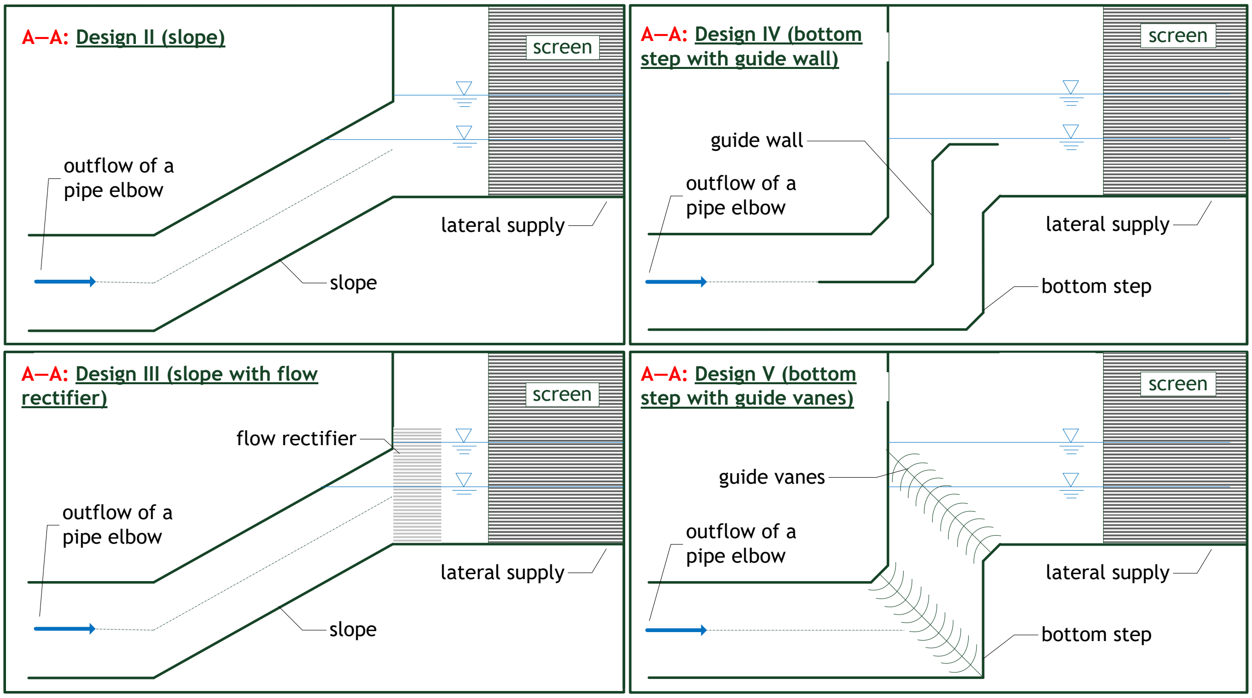

Figure 4: Longitudinal sections A-A of investigated riser-designs II-V.

The results of the velocity measurements are presented in **Figure 5**. Velocity fields of riser outflows are illustrated in the left and middle columns of **Figure 5**. The results show that each riser outflow is characterised by an inhomogeneous velocity distribution in measuring plane 1. Whereas designs II and III are generating a field of maximum velocities at the walls and the bottom of the riser, the outflow of designs IV and V is characterised by different flow behaviour. In both cases the area of maximum velocity is located in the centre of the flow field. A planar jet exists in case of design IV and a circular jet in case of design V. Furthermore, all riser-outflows differ in terms of swirl and homogenisation between measuring field 1 and 2. In terms of the screen outflow, homogeneous velocity distributions were achieved in case of the riser design II and IV. On the other hand inhomogeneous distributed screen outflows were produced by design III and V. Consequently, a difference between the investigated riser outflows exists: whereas some inhomogeneous distributed riser outflows are generating a homogeneous screen outflow others are generating an inhomogeneous one. In order to explain this flow-behaviour, the turbulent time series of the different riser outflows (at the same location inside the flow field) are considered. In **Figure 6**, a comparison between both slope-designs (II and III) is presented. Obviously the time lines differ in the temporal velocity fluctuations under identical boundary conditions and constant flow rate. While the outflow of the design II is characterised by a more turbulent flow, the same design with a conducted flow rectifier (design III) is much calmer. Turbulent fluctuations play an important role concerning mixing processes (Kraatz, 1975). The homogenisation process strongly depends on these mixing processes. In context of the presented riser, fine structures as the flow rectifier prevent necessary mixing processes for homogenisation. In view of designs IV and V, the same flow behaviour can be identified, because mixing seems to work out better in case of the coarse guide wall than in case of small guide vanes.

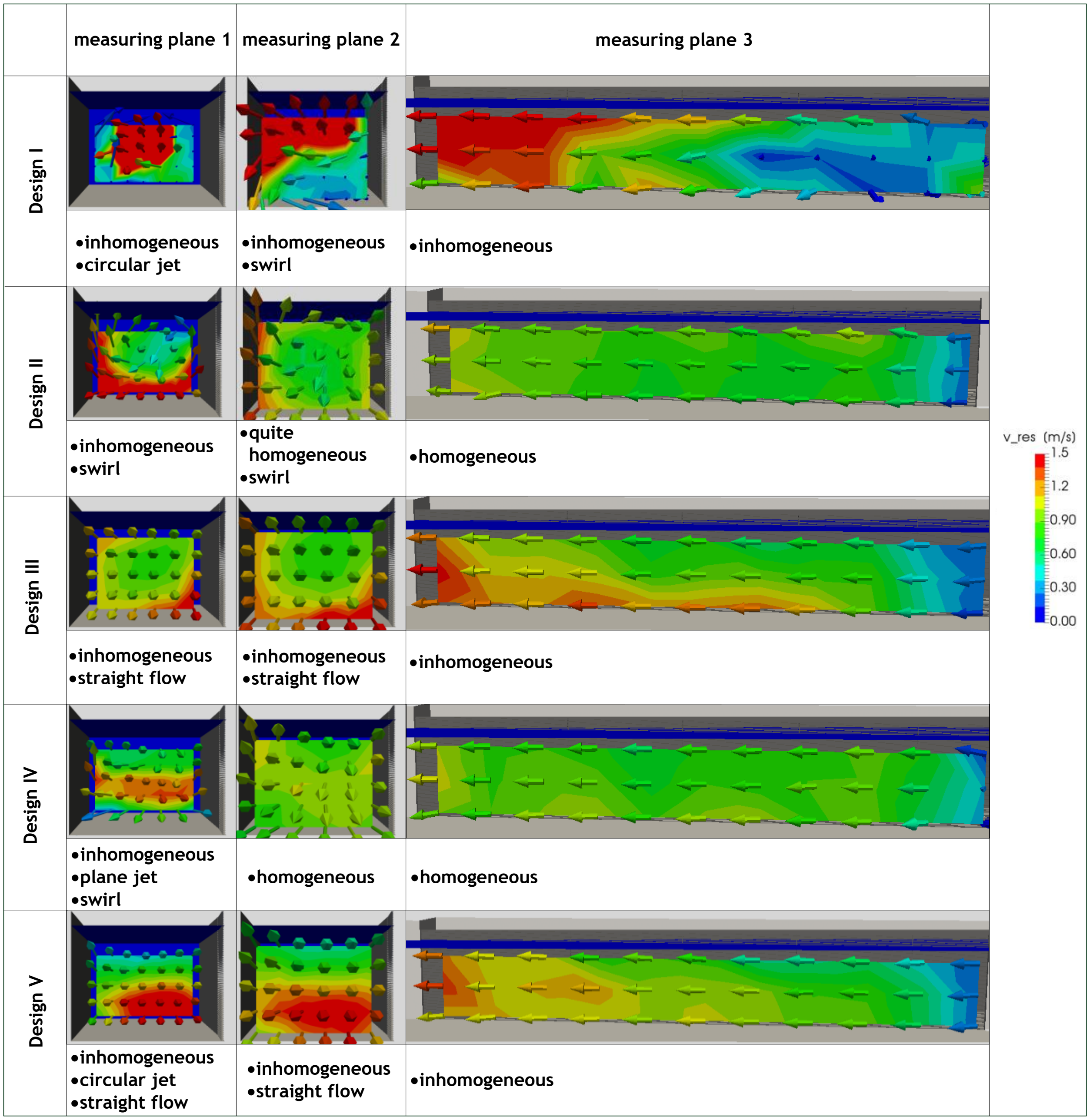

Figure 5: Results of riser- and screen-outflow velocity-measurement.

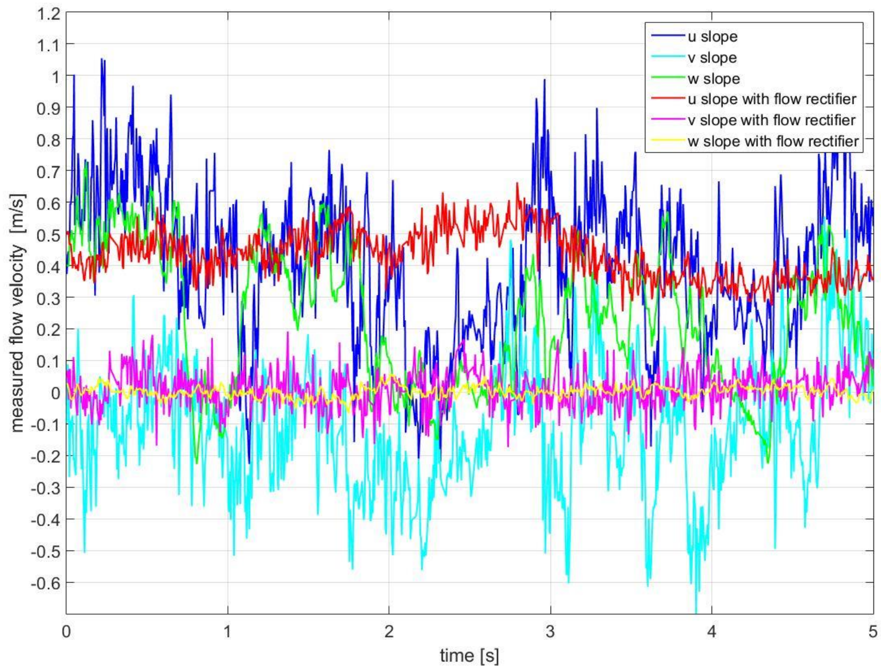

Figure 6: Turbulent time series of riser outflow velocities (components u, v and w) in case of "slope design" (design II) and "slope with flow-rectifier design" (design III) at the same measuring point.

Table 1: Flow characteristics of the investigated lateral supply structure with different risers.

		Design I	Design II	Design III	Design IV	Design V
$IH(v_{res})$ [%]	measuring plane 1	110	45	20	37	43
	measuring plane 2	68	33	23	11	32
	measuring plane 3	60	29	41	21	36
$H(v_{res})$ between measuring plane 1 and 2 [%/m]		21	11	-3	13	6
$TI(v_{res})$ [%]	measuring plane 1	97	74	22	81	47
	measuring plane 2	134	25	20	55	39
	measuring plane 3	65	45	37	35	41
$C(v_{res})$ between measuring plane 1 and 2 [%/m]		-18	2	2	14	4

To quantify these flow phenomena, the parametres IH, H, TI and C were computed using Eq. (1) to (4) for each velocity field (**Table 1**). The flow behaviour described above is represented by the given parametres. Homogeneous flow is characterised by lower IH-values while inhomogeneous flow is characterised by higher IH-values (same for TI). Additionally, results show that coarse guiding structures affect high TI-values and fine guiding structures affect low TI-values. Further homogenisation and calming are also reflected comprehensively by H and C. The best screen-outflow (lowest inhomogeneity- and turbulence intensity) was achieved by design IV. In this case, homogenisation and calming of the flow were created by a riser-outflow in shape of a planar jet (**Figure 5**). In comparison to the other cases, the planar jet produced a quite effective self-homogenisation and calming. The worst screen outflow (highest inhomogeneity and turbulence intensity) of the designs II-V occurred with the design II because mixing processes were mitigated by the rectifier extensively.

4. Conclusion

The purpose of the present study was to optimise a vertical connection (riser) between a deeply arranged transmission-line and a supply structure for the discharge of auxiliary water in a fishway. Riser designs must provide an outflow, which enable the formation of a homogeneous supply flow. The investigation shows that riser designs have to allow mixing processes (turbulence) inside the riser outflow with the purpose to create a homogenisation of flow. This can be achieved by coarse guiding structures inside the riser or even no guiding structure. Additionally, the study showed that fine guiding structures are able to mitigate mixing processes and are not suitable in case of inhomogeneous flow. Good results regarding homogenisation and calming of the flow were achieved with the riser design II (slope) and IV (bottom-step with guide-wall). Fine-guiding structures (e.g. flow rectifier) may be useful with the requirement that flow is already distributed homogeneous upstream of the riser. Further, the parametres inhomogeneity; homogenisation and calming of flow were defined with the purpose to assess the flow in supply structures. The present analysis demonstrates that these parametres are appropriate to quantify hydraulic processes in auxiliary water systems.

In general, flow in supply structures depends on many parametres like upstream hydraulic conditions inside the transmission-line, the arrangement of the connection between transmission-line and supply structure or guiding structures. Further, the present investigation shows that systematic studies of these influences are necessary to establish general design recommendations.

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